Robust Autonomous Aerobraking Strategies

9th International Planetary Probe Workshop

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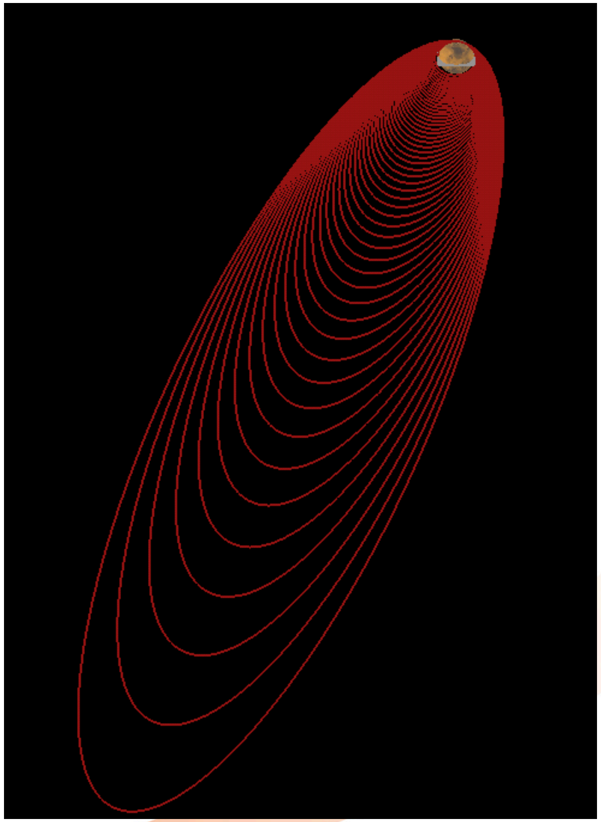
Outline

- Introduction & mission scenario
- High-fidelity aerobraking simulator (HiFAS)
- AOCS for aerobraking
- Autonomous aerobraking: level 1 & level 2
- Safe mode for aerobraking
- Conclusions and future work

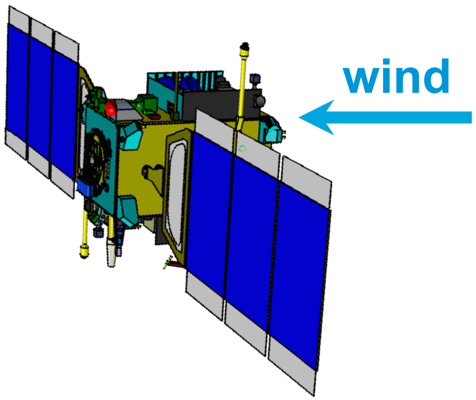
Introduction

- Aerobraking consists in using atmospheric air drag in order to reduce the orbit's apoapsis altitude
  - Allows significant mass savings with direct benefits to mission design
  - Aerobraking has been performed on several US missions to Venus and Mars, and an European experiment is planned in 2014 on VEX
  - Baselined on recent ESA system studies (MarsNEXT, MSR Orbiter)
- However, aerobraking remains a challenging phase:
  - High cost due to ground operations heavy workload
  - Risk of spacecraft component over-heating, or even mission loss
- The main objective of the study is to define and select aerobraking strategies aiming at:
  - Gradually increasing aerobraking autonomy level
  - Guaranteeing aerobraking robustness
- Performed in the frame of ESA study "Robust Autonomous Aerobraking Strategies"



Aerobraking mission scenario

- ESA MarsGen is to be used as reference mission
  - ESA system study performed in 2009
  - Mars network science mission (launch 2020 – 2022)
  - Follow-up study to MarsNEXT



- The selection of the aerobraking scenario is the result of a trade-off between:
  - Spacecraft characteristics
  - Propellant consumption
  - Aerobraking aggressiveness
  - Aerobraking duration

- The resulting operational point is as follows:
  - Ballistic coefficient of 25 kg/m²
  - Initial apoapsis altitude at 67500km
  - Peak dynamic pressure at 0.5 N/m²
  - These conditions allow limiting the duration of aerobraking to 6 months (including margins)

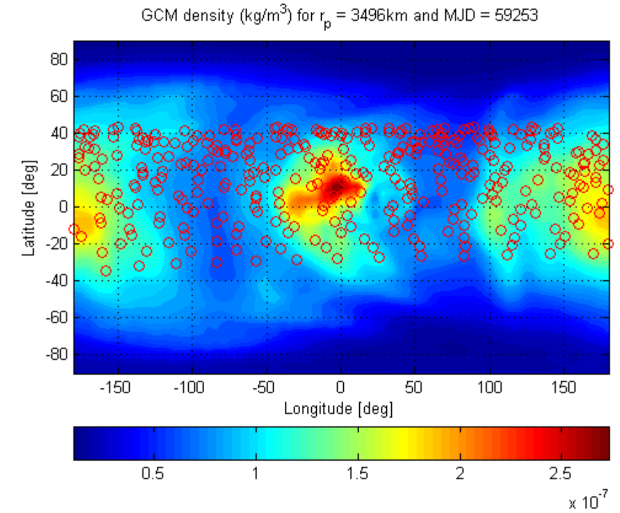
B [kg/sqm]	p-peak [N/sqm]	q-peak [W/sqm]	Phase dur. [d]	Init. apocentre alt. [km]	Apocentre lowering man. [m/s]	Pericentre control [m/s]	Apocentre raising [m/s]
	0.3	1350	150	35000	132	22	99
25	0.5	2250	150	67500	34	14	100
	0.7	3200	140	96000	0	11	101
	0.3	1300	150	23500	217	31	99
35	0.5	2200	150	43000	96	20	100
	0.7	3200	150	67000	35	14	101
	0.3	1280	150	16000	321	39	99
50	0.5	2200	150	28000	177	27	100
	0.7	3150	150	41500	102	21	101

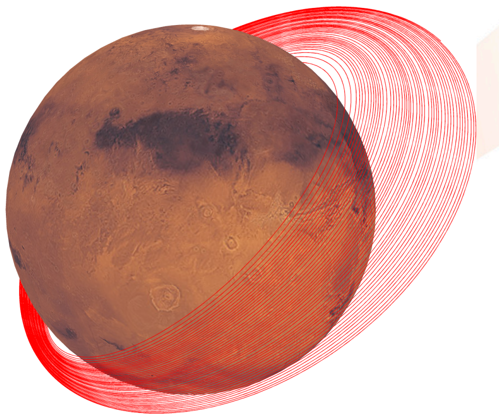
High-fidelity Aerobraking Simulator (HiFAS)

- Main objective is to implement, validate and evaluate autonomous aerobraking strategies

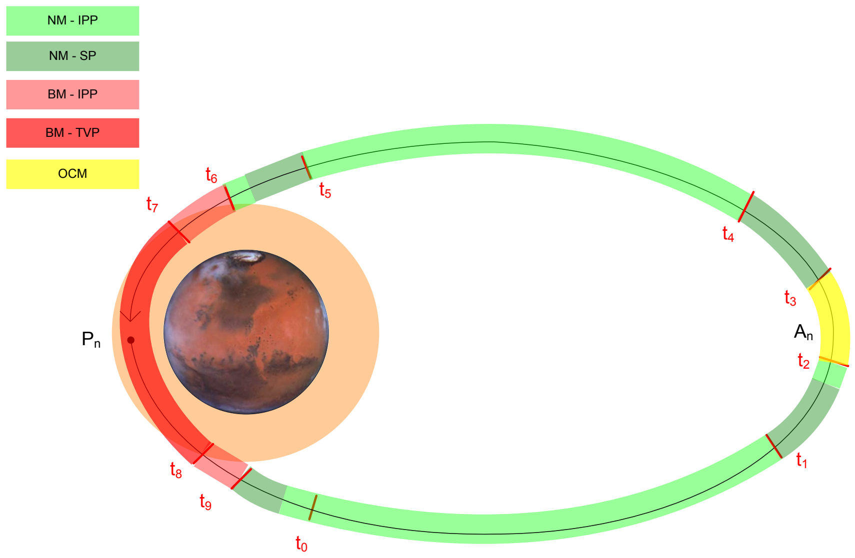
- Environment modelling is critical in order to properly capture the effects that drive the aerobraking phase
  - Mars atmosphere density variations
    ➔ high-fidelity Mars atmosphere models including both short-scale and long-scale perturbations: Mars Climate Database, General Circulation Model
  - Aerobraking orbit evolution
    ➔ 20x20 Mars gravity field and Solar gravity
  - Temperatures of critical elements
    ➔ S/C thermal model, for both MLI and solar arrays
  - Power status (e.g. for safe mode validation)
    ➔ S/C battery charge model

- Management of different regimes (drag/vacuum)
  - Implementation of a « variable scheduler » in order to manage different simulation time steps and minimize computation time
  - Enables simulations from one atmospheric pass (~1000s) up to typically one week for full « end-to-end » validation

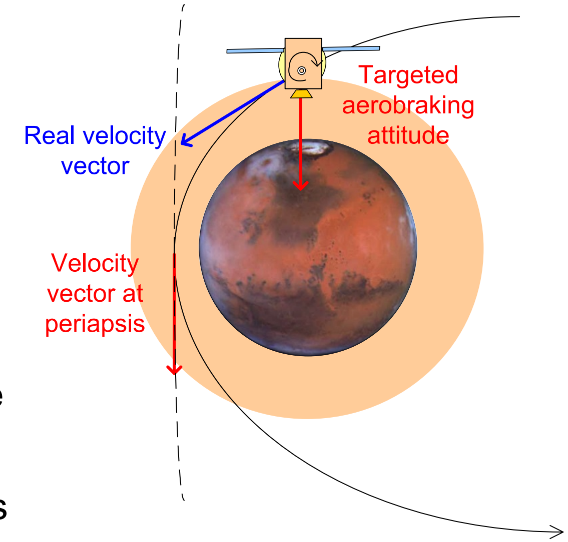




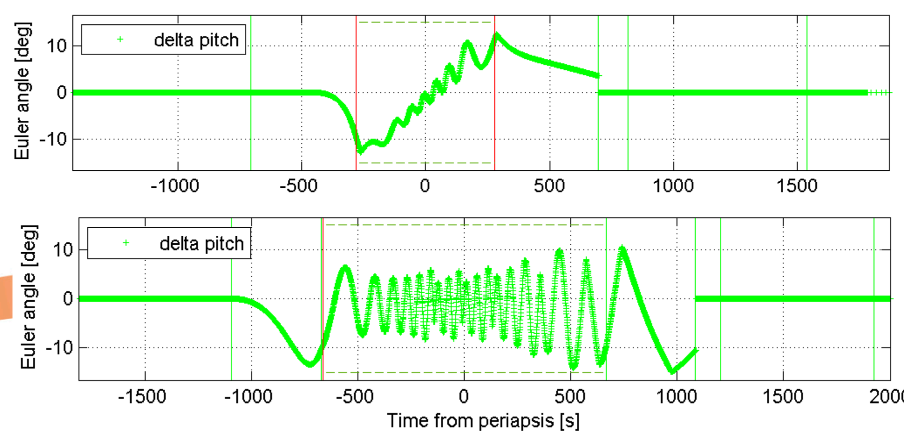
AOCS for aerobraking:
AOCS modes and sequences



AOCS for aerobraking: AOCS design

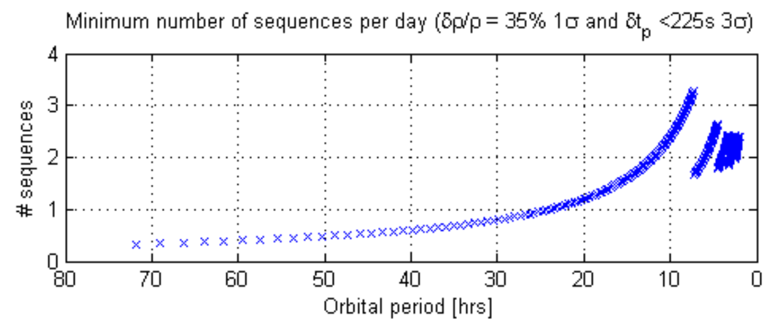


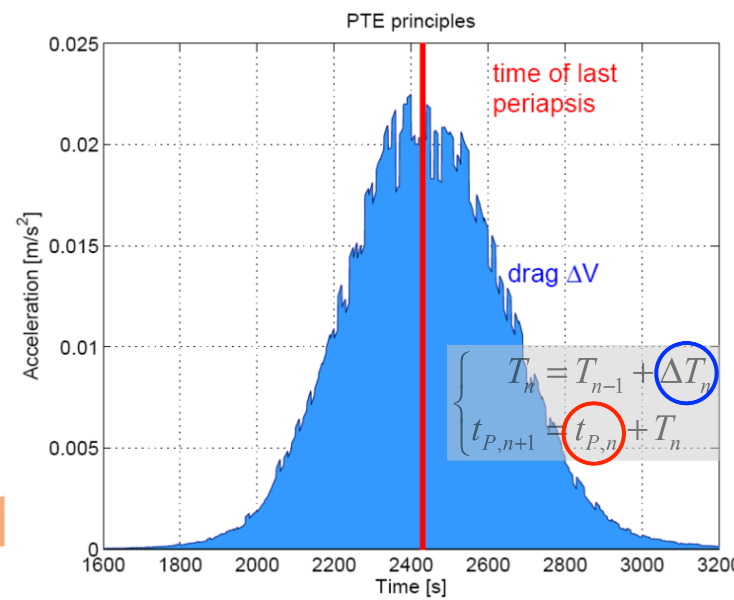
- Attitude control is based on an aerodynamically stable S/C configuration
  - Avoid fighting the aerodynamic torque
  - Wide deadband, thruster-based control as safeguard
- Guidance is inertial until final stage of aerobraking, then time-varying as the orbit becomes circular
  - Time-varying guidance generates timing constraints, since the attitude profile must be close enough to the actual velocity vector
  - For instance, a 15 deg maximum attitude error leads to a 180s periapsis timing error in the end of aerobraking (worst case)
  - In the case of inertial pointing, this timing constraint is relaxed
- The proposed AOCS baseline is validated by simulations
  - Attitude is always kept within ± 15 deg around guidance profile
  - Consumption remains reasonable (a few grams per pass)
  - Validity of inertial guidance in the beginning of aerobraking is confirmed



Autonomy level 1: Motivation and design

- Because of atmospheric variability and misknowledge, AOCS sequences generated by the ground are quickly out-of-sync with actual orbit events
  - May lead to extra-propellant usage or unsafe situations
  - Heavy operational workload in order to ensure proper timing
  - But orbit timing may be detected autonomously via onboard accelerometers
- Objectives of autonomy level 1:
  - Shift upcoming drag sequences in time in order to match actual orbit events, based on onboard atmospheric sensing ➔ Periapsis Time Estimator
  - Protect the spacecraft against excessive heat loads not foreseen by ground ➔ Immediate Action procedure
- Principles of the Periapsis Time Estimator:
  - Firstly, the time of last periapsis is estimated from drag barycenter
  - Then accumulated drag ⌧V is used to update orbital period and predict time of next periapsis
  - Thus after each drag pass, the timing of the next orbit is autonomously corrected, without any error growth





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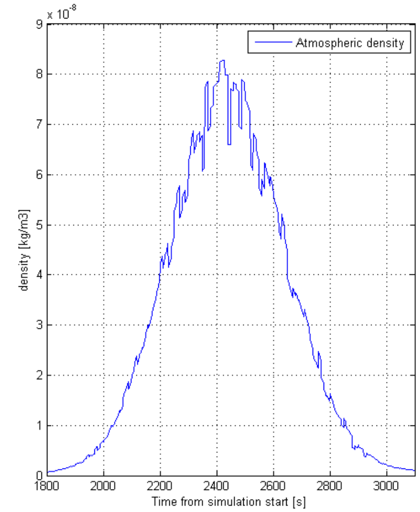
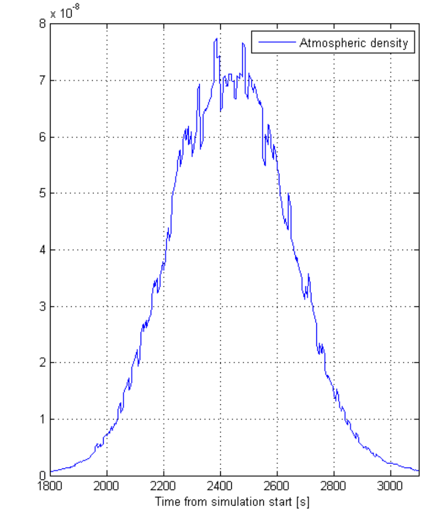
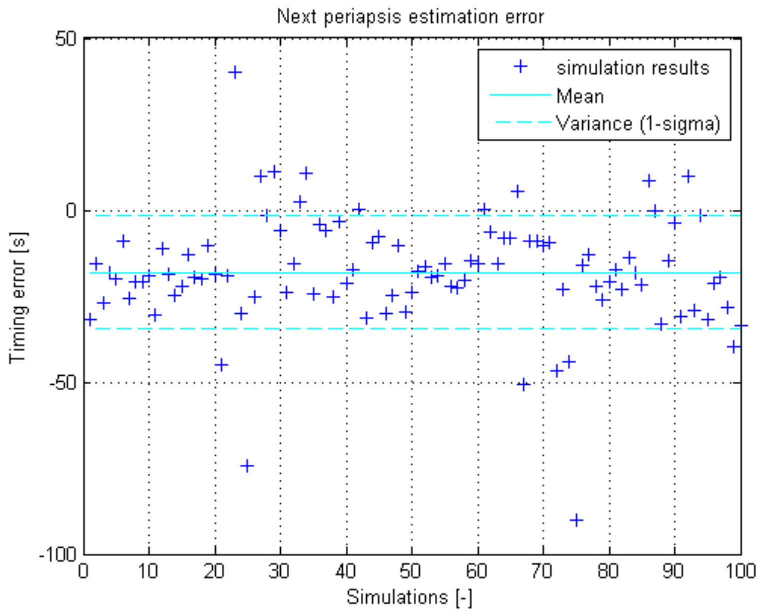
Autonomy level 1: Simulation results and conclusions

- The Periapsis Time Estimator (PTE) was validated on a wide range of conditions
  - Different orbital geometry cases
  - Varying atmospheric conditions, including both long-scale and short-scale atmospheric perturbations
  - Varying sensor noises
- The PTE predicts the time of next periapsis with the required accuracy (< 180s) over 3 days and more
  - Performances improve over aerobraking as sensitivity to drag ΔV estimation error decreases
  - Robustness to atmospheric perturbations has been demonstrated
- Additional lessons learned:
  - The implementation of a corrective factor to account for non-instantaneous drag ΔV is required
  - Calibration of accelerometers bias before each pass is necessary (in the beginning of aerobraking)

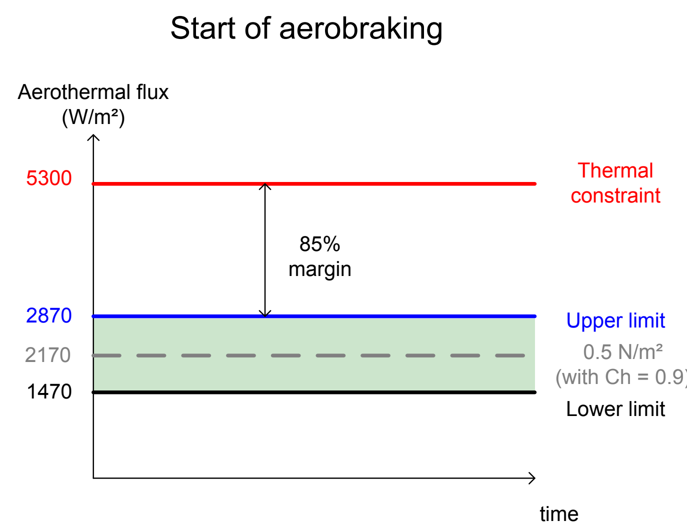


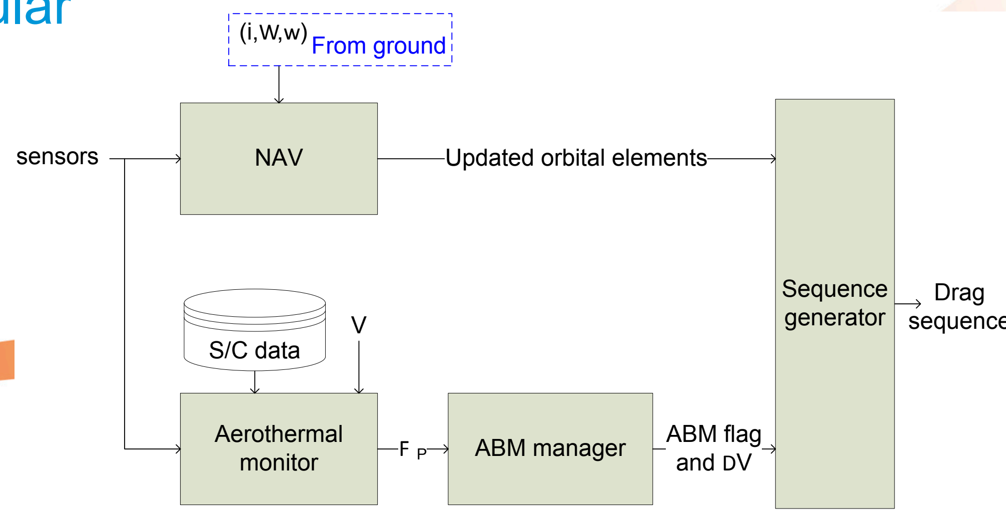




Autonomy level 2: Motivation and design

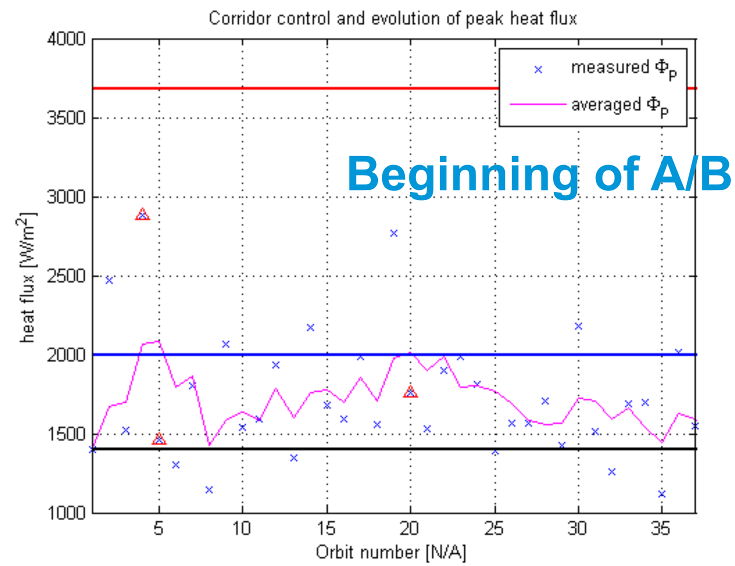
- Main objective: extend S/C autonomy by transferring additional activities onboard
  - Relieve the ground from most low-level activities, so that it may focus on high-level activities
  - Target autonomy horizon of **one week** for identified activities
- Two activities were considered for onboard implementation:
  - Drag sequences generation
  - Corridor control, i.e. ABM analysis, decision-making and selection
- The ground still performs regular orbit determination and high-level activities, such as:
  - Monitor aerobraking progress
  - Update aerobraking corridor
  - Atmosphere monitoring and trending
  - Modelling updates

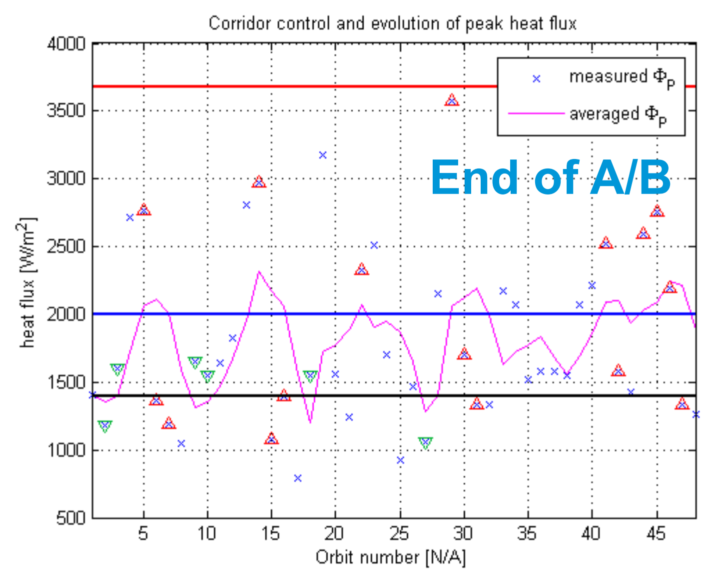




Autonomy level 2: Simulation results and conclusions

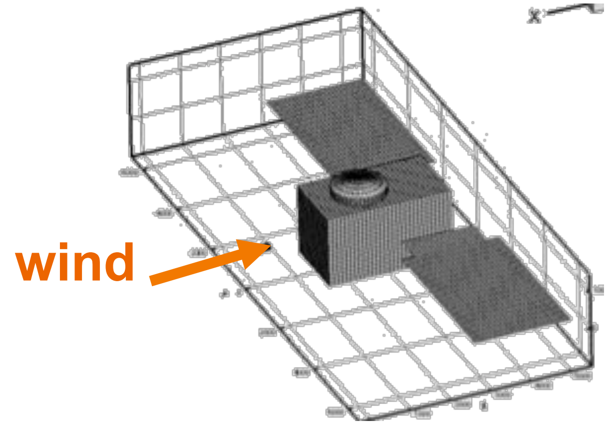
- The algorithms of level 2 were implemented and validated over one week, with satisfactory results
  - Almost no excessive heat flux occurrences
  - Achieved dynamic pressure peak is between 0.49 N/m² and 0.76 N/m², exceeding the target 0.5 N/m²
  - Reasonable ΔV consumption for corridor control, extrapolated to ~40m/s over 6 months in worst case
  - Frequency of the required ground updates to support onboard navigation has been preliminary estimated (from > 7 days to ~3 days in the end)
- The simple approach to autonomous corridor control works
  - Minimal onboard navigation, simple heat flux control approach
  - Potentially removes the need for complex onboard propagator, models, fully autonomous navigation

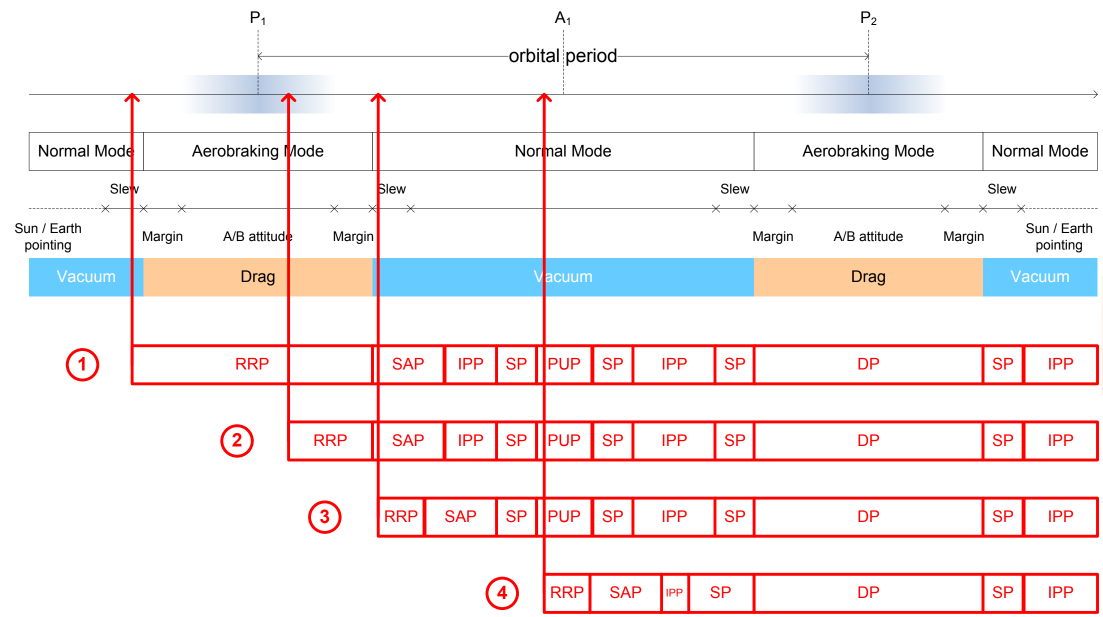




Aerobraking safe mode

- Classical safe mode for interplanetary missions may lead to arbitrary attitude in atmospheric flow ➔ dynamics, thermal, orbital decay issues
- Trade-off between different solutions led to the combination of a low-drag configuration and pop-up ΔV
- Design validated by simulations, based on thermal, power, orbital decay criteria





1: safe mode just before atmospheric entry; not enough time to go to aerobraking configuration
2: safe mode during atmospheric pass
3: safe mode right after atmospheric pass
4: safe mode around apoapsis ; not enough time to perform pop-up boost at apoapsis

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Conclusions and future work

- The AOCS design for aerobraking has been validated
- The PTE has been validated, enabling autonomy level 1
- The feasibility of the simple approach to autonomous corridor control has been demonstrated
- The proposed safe mode design has been validated by simulations, ensuring S/C safety
- The immediate action procedure triggered in case of thermal alarm was validated, reducing the experienced temperatures at the next periapsis even in the case of a global dust storm
- Next step: validate and evaluate autonomy algorithms during VEX aerobraking experiment (2014) ➔ first demonstration of their operational capabilities

Thank you for your attention !